SPEED SIGNAL VARIANCE DETECTION FAULT SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

[001] The present invention generally relates to turbine engines and, more particularly, to a method and system used in electrical control sensors for shaft speed signal frequency change rate tests.

[002] Compressor and load shaft speeds are the primary control parameters of gas turbine engines. Accurate speed measurement is essential for proper engine control. In modern engines with electronic control systems, shaft speeds are typically measured using passive variable reluctance magnetic speed sensors, which sense passing of gear teeth or similar objects. The sensors output an electrical signal to the gas turbine electronic control unit (ECU), with signal frequency proportional to the shaft speed (i.e., passing speed of the gear teeth). The ECU measures the speed by measuring the frequency of the speed pickup signal. The ECU typically conducts reasonableness tests to insure the accuracy of the signal before using it. These may include sensor impedance tests (to check whether the electrical characteristics of the sensor appear normal), and signal frequency range and change rate tests (to check whether the resulting signal characteristics appear normal, within the expected range and not changing at an unreasonable rate).

[003] The conventional signal frequency change rate tests used to detect intermittent or "in-range" failures are unreliable because they either often detect failures that do not truly exist (false alarms) or, in order to avoid generation of false alarms, they miss real failure events. There are four typical failure modes that need to be addressed by signal frequency change rate type tests. First failure mode includes intermittent electrical sensor failures that cause a noisy signal. The other three failure modes include "in-range" failures. Second

failure mode includes internal sensor failures which can cause "multiple crossings" or cases where higher than normal speeds are read occasionally. Third failure mode includes damaged gear teeth, shaft runout or excessive speed pickup installation gaps, and can cause "missed teeth" and resultant speed measurement errors. Some conventional controllers even have added sophisticated hardware circuits to detect "missing teeth". On turbofans, the fourth failure mode is a catastrophic engine failure event called a "blade out", which causes the controller to perceive speed incorrectly and fuel the engine up.

[004] As can be seen, there is a need for a method and system for implementing signal frequency change rate tests, useable for detection of four intermittent or "in-range" failure modes discussed above, which is more reliable and less complex.

SUMMARY OF THE INVENTION

[005] In one aspect of the present invention, a system useable in electrical control sensors for shaft speed signal frequency change rate tests, detects intermittent or "in-range" failures. It has means for measuring frequency of a shaft speed signal; means for estimating a short-term variance (standard deviation) of the measured signal using the equation: $Var[x] = E[x^2] - E^2[x]$, where $E[x^2]$ is an estimated average of the squared measured signal over a short time interval, and $E^2[x]$ is a squared estimated average of the measured signal over a short time interval; means for comparing the estimated short term variance with a predefined variance limit for a predefined amount of time; and means for deeming the measured signal invalid, if the estimated variance exceeds the predefined variance limit for the predefined amount of time.

[006] In another aspect of the present invention, a system useable in

electrical control sensors for shaft speed signal frequency change rate tests, detecting intermittent or "in-range" failures, has means for measuring frequency of a shaft speed signal; means for calculating a rate of change (time derivative) of the measured signal; means for estimating a short-term variance (standard deviation) of the measured signal rate of change using the equation: $Var[x] = E[x^2] - E^2[x]$, where $E[x^2]$ is an estimated average of the measured signal squared rate of change over a short time interval, and $E^2[x]$ is a squared estimated average of the measured signal rate of change over a short time interval; means for comparing the estimated short term variance with a predefined variance limit for a predefined amount of time; and means for deeming the measured signal invalid, if the estimated variance exceeds the predefined variance limit for the predefined amount of time.

[007] In a further aspect of the present invention, a method useable in electrical control sensors for shaft speed signal frequency change rate tests, detecting intermittent or "in-range" failures, has the steps: (a) measuring frequency of a shaft speed signal; (b) estimating a short-term variance (standard deviation) of the measured signal using the equation: $Var[x] = E[x^2] - E^2[x]$, where $E[x^2]$ is] is an estimated average of the squared measured signal over a short time interval, and $E^2[x]$ is a squared estimated average of the measured signal over a short time interval; (c) comparing the estimated short term variance with a predefined variance limit for a predefined amount of time; and (d) if the estimated variance exceeds the predefined variance limit for the predefined amount of time, deeming the measured signal invalid.

[008] In yet another aspect of the present invention a method useable in electrical control sensors for shaft speed signal frequency change rate tests, detecting intermittent or "in-range" failures, has the steps: (a) measuring frequency of a shaft speed signal; (b) calculating a rate of change (time derivative) of the measured signal; (c) estimating a short-term variance

(standard deviation) of the measured signal rate of change using the equation: $Var[x] = E[x^2] - E^2[x]$, where $E[x^2]$ is an estimated average of the measured signal squared rate of change over a predefined short term, and $E^2[x]$ is a squared estimated average of the measured signal rate of change over the predefined short term; (d) comparing the estimated variance with a predefined variance limit for a predefined amount of time; and (e) if the estimated variance exceeds the predefined variance limit for the predetermined amount of time, deeming the measured signal invalid.

[009] These and other features, aspects and advantages of the present invention will become better understood with reference to the following drawings, description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 depicts a top level flowchart of a method for estimation of the short-term variance of a signal, according to a preferred embodiment of the present invention.

[0011] Figure 2 depicts a block diagram of a signal variance detection logic used for estimation of the short-term variance of a signal according to a preferred embodiment of the present invention.

[0012] Figure 3 depicts a flowchart of a method for estimation of the short-term variance of a signal rate of change according to a preferred embodiment of the present invention.

[0013] Figure 4 depicts a block diagram of a signal variance detection logic used for estimation of the short-term variance of a signal rate of change according to a preferred embodiment of the present invention.

[0014] Figure 5 depicts a functional graph of the latching counter according to a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0015] The following detailed description is of the best currently contemplated modes of carrying out the invention. The description is not to be taken in a limiting sense, but is made merely for the purpose of illustrating the general principles of the invention, since the scope of the invention is best defined by the appended claims.

[0016] The present invention includes a speed signal variance detection fault logic system and method, available for signal frequency change rate tests, used to detect intermittent or "in-range" failures. It is more reliable than reasonableness rate tests, due to better failure detection with fewer false alarms. Moreover, it is less complex because it avoids the use of complex missing tooth detectors.

[0017] Although developed for compressor and load shaft speed parameters of gas turbine engines, the method and system of the present invention can be applied for testing other sensed signals, such as EGT probes signals, presently using other signal change rate tests.

[0018] The preferred methods of the present invention either calculate an estimate of the variance (standard deviation) of the tested signal, or calculate an estimate of the variance of the rate of change of the tested signal. Due to oversampling, valid engine signals or signals rate of change do not change much and the change is smooth. Thus, they show a high autocorrellation and small variance over the short term. Erratic signals, such as signals corrupted by electrical noise, show rapid changes during certain failures, the signal becomes much less correllated and thus the variance increases. For the four speed signal failure modes discussed above, the speed signal becomes much less correllated and the variance of the signal or signal rate of change

increases dramatically, allowing detection by a simple algorithm.

Variance of a signal x is defined by the equation:

$$\text{Variance}[x] = E\,[x^2] - E^2[x]$$

where E is an expectation operation used to estimate average of a signal x.

[0019] One method embodiment of the present invention estimates the short-term variance of a signal using the following algorithm:

$$\text{Variance[signal]} = \text{Filtered}\,[\,(\text{signal}\,)^{\,2}\,] - (\,\text{Filtered [signal]}\,)^2$$

In this algorithm the approximate value of the expectation operation (E), which is the estimated short term average a signal x, is obtained by an averaging filter.

[0020] Figure 1 illustrates a top level flowchart of this method embodiment of the present invention, for estimation of the short-term variance of a signal. In step 100, the tested input signal is squared. In step 110, an estimate average of the squared input signal is obtained via filtering, generating an estimate of the average of x^2 over the short term. In step 120, an estimate average of the input signal is obtained via filtering. It is then squared, generating a squared estimate of the average of x over the short term, for use in step 130. In step 130, an estimate of the short term variance is calculated, using the equation for variance: $\text{Var}[x] = E[x^2] - E^2[x]$, where E is the expectation operator, or average. In step 140, the estimated variance value is compared with a predefined variance limit and latching counter of the rate test. In step 150, it is tested whether the estimated variance exceeds the predefined limit for a given amount of time. If not, the test is over in step 160. If the estimated variance exceeds the predefined limit for a given amount of time, in step 170, the signal is

deemed to be inaccurate and invalid because the variance is too high to be that of a real signal.

[0021] Figure 2 illustrates a block diagram of a signal variance detection logic which implements the method embodiment of the present invention, used for estimation of the short-term variance of a signal. In a multiplier 200, the tested input signal is squared. In element 210, an estimate average of the squared input signal is obtained via filtering. In element 220, an estimate average of the input signal is obtained via filtering. In multiplier 225, this signal is squared. In element 230, an estimate variance is calculated by subtraction of the two estimated signals obtained from elements 210 and 225. In element 240, the calculated estimated variance value is compared with a predefined variance limit of the rate test. In latching counter (timer) 250, it is tested whether the estimated variance exceeds the predefined variance limit for a predefined amount of time. If the estimated variance exceeds the predefined limit for a given amount of time, the signal is deemed to be inaccurate and invalid because the variance is too high to be that of a real signal.

[0022] In another method embodiment of the present invention, illustrated in Figure 3, an estimated variance of the signal rate of change is calculated. For example, for engine compressor fans having speed signal Nfan, it is preferable to calculate the estimated variance of the speed signal rate of change d(Nfan)/dt, using the equation:

$$\text{Variance}[d(\text{Nfan})/dt] = \text{Filtered}\ [\ (d(\text{Nfan})/dt)^2\ ] - (\text{Filtered}\ [d(\text{Nfan})/dt]\ )^2$$

In this algorithm, the approximate value of the expectation operation (E), which is the estimated short term average signal x, is obtained by a filter.

[0023] Figure 3 illustrates a flowchart of this method embodiment of the

present invention, for estimation of the short-term variance of a signal rate of change. This flowchart shows variance detection as actually implemented in AS900. Thus, it shows several preliminary testing steps 300-304. In step 300, a sensor is read to obtain the tested signal. In step 302, the sensor is tested. In step 304, it is determined whether the reading is valid and, if not, step 370 is executed. If valid, in step 306, the rate of change of the signal is calculated. In step 308, the tested input signal is squared. In step 310, an estimate average of the squared input signal is obtained via filtering, generating an estimate of the average of x^2 over the short term. In step 320, an estimate average of the input signal is obtained via filtering. It is then squared, generating a squared estimate of the average of x over the short term, for use in step 330. In step 330, an estimate of the short term variance is calculated using the equation for variance: $Var[x] = E[x^2] - E^2[x]$, where E is the expectation operator, or average.

[0024] In step 340, the estimated variance value is compared with a predefined variance limit and latching counter of the rate test. In step 350, it is tested whether the estimated variance exceeds the predefined limit for a given amount of time. If not, the test is over in step 360. If the estimated variance exceeds the predefined limit for a given amount of time, in step 370, the signal is deemed to be inaccurate and invalid because the variance is too high to be that of a real signal.

[0025] Figure 4 illustrates a block diagram of a signal variance detection logic which implements the method embodiment of the present invention, used for estimation of the short-term variance of a signal rate of change. In element 400, the rate of change (time derivative) of an input signal is calculated. In a multiplier 402, the tested input signal rate of change is squared. In element 410, an estimate average of the squared input signal rate of change is obtained via filtering. In element 420, an estimate average of the input signal rate of change is obtained via filtering. In multiplier 425, this signal is squared. In

element 430, an estimate variance is calculated by subtraction of the two estimated signals obtained from elements 410 and 425. In element 440, the calculated estimated variance value is compared with a predefined variance limit of the rate test. In latching counter (timer) 450, it is tested whether the estimated variance exceeds the predefined variance limit for a predefined amount of time. If the estimated variance exceeds the predefined limit for a given amount of time, the signal is deemed to be inaccurate and invalid because the variance is too high to be that of a real signal.

[0026] Similar approaches can be used for other gas turbine signals, estimating either the variance of the signal or the variance of the rate of change of the signal, and then comparing the estimated variance with a predefined limit to detect signal failure.

[0027] The preferred embodiments of the present invention of may be embedded either into the gas turbine ECU software application or in the ECU hardware circuitry.

[0028] An estimate of the average short term variance of an input signal or rate of change is preferably obtained via analog or digital filters. The preferred system embodiments of the present invention preferably use filters which are simple first order lags, but higher order filters or other signal averaging modules may be used as well. Two digital filter methods may be used in the present invention. The first method includes calculation of a rolling average. The second method includes calculation of a filtered value of the input stream.

[0029] The method of calculating a rolling average of the z most current signal input reading drops the oldest reading from the average each time a new reading is available. The calculation is performed according to the equation:

$$y(n) = [x(n) + x(n-1) + x(n-2) + \ldots + x(n-(z-1))] / (z)$$

where: y(n) is the current estimate of the average at iteration n, x(n) is the current value of the input to the filter, x(n-1) is the previous value of the input to the filter, x(n-2) is the 2nd last value of the input to the filter, and x(n - (z-1)) is the (z-1)th last value of the input to the filter.

[0030] To calculate a filtered value of the input stream, two types of filters can be used in the digital embodiments: finite impulse response filters and infinite impulse response filters. Finite impulse response (FIR) filters calculate a weighted rolling average of the z most current readings; this is similar to a rolling average but with weights. The weights allow tailoring of the frequency response of the averaging, according to the equation:

$$y(n) = [w1\ x(n) + w2\ x(n-1) + w3\ x(n-2) + \ldots + wz\ x(n-(z-1))]/(w1 + w2 + w3 \ldots + wz)$$

where: y(n) is the current estimate of the average at iteration n, x(n) is the current value of the input to the filter, x(n-1) is the previous value of the input to the filter, x(n-2) is the 2nd last value of the input to the filter, x(n - (z-1)) is the (z-1)th last value of the input to the filter, and w1-wz are weighting coefficients used to tailor the frequency or time response characteristics of the filter.

[0031] Infinite impulse response (IIR) filters are digital embodiments of standard analog filters. IIR filters weight recent input data more strongly than older data. As a datum become older and older, its weight dwindles to essentially zero.

$$y(n)=a1\ y(n-1) + a2\ y(n-2) + \ldots + az\ y(n-z) + b1\ x(n) + b2\ x(n-1) + \ldots bw\ x(n-(w-1))$$

where: y(n) is the current estimate of the average at iteration n, y(n-1) is the last value of the estimate of the average, y(n-z) is the (z-1)th last value of the

estimate of the average, x(n) is the current value of the input to the filter, x(n-1) is the last value of the input to the filter, x(n-(w-1)) is the (w-1)th last value of the input to the filter, a1-az and b1-bw are weighting coefficients used to tailor the frequency or time response characteristics of the filter. The weighting coefficients sum to 1.0.

[0032] Analog filter circuitry embodiments of the invention will typically use traditional analog filters that function similarly to digital IIR filters.

[0033] The preferred embodiments of the present invention were implemented in the AS900, and utilize a simple digital IIR filter for estimating the short term averages, according to the equation:

$$y(n) = 0.818\, y(n-1) + 0.091\, x(n) + 0.091\, x(n-1)$$

where: y(n) is the current estimate of the average, y(n-1) is the last value of the estimate of the average, x(n) is the current value of the input to the filter, x(n-1) is the last value of the input to the filter, and x and y are calculated, depending on the sample rate (N1), at a 50ms or 100ms rate. This results in a shift in frequency response of the averager/filter as the sampling rate changes, but produces the desired result in the AS900 N1 speed case.

[0034] Preferably, the latching counter (timer) 250, 450 of the present invention utilizes a unique algorithm that times out faster if the input is constantly true, as shown in Figure 5. The timer times out at a slower rate when the input is true “most of the time". Thus, the rate is dependent on the proportion of time the input is true.

[0035] The preferred embodiments of the present invention may be used in two ways. Firstly, they may be used on-line to detect and accommodate failures as they occur, in order to insure continued safe engine operation, as would be the case with a speed signal failure or blade out event. Secondly,

they may be used off-line to predict future failures and allow for maintenance before a future failure occurs, as might be the case with typical gas turbine hot section temperature probes signals that are averaged electrically in the probe assembly. There, although operation is not initially affected as the individual probes fail, variance increases with each probe failure. Moreover, the preferred embodiments of the present invention may be used to determine the validity of sensor signals for any electronic control sensor, such as automotive oxygen content sensors, chemical factory mixture temperature/pressure sensors, etc.

[0036] It should be understood, of course, that the foregoing relates to preferred embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.